AIAA 80-0884R

Tropospheric Effects of Satellite Power Systems

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The construction and operation of a system of solar power satellites would be expected to have a variety of effects on the troposphere. The launching of large space vehicles affects the air quality in the vicinity of the launch site; and the ground cloud associated with such a launch is known to stimulate the growth of water clouds under some circumstances. The transmission of power from the satellite to the Earth's surface may affect certain meteorological parameters in the vicinity of the rectenna site. These and other effects are discussed in reference to the proposed solar power satellite system.

Introduction

THE proposed satellite power sytem (SPS), as described in the concept development and evaluation program reference system report,[1] would give rise to a large number and wide variety of atmospheric effects. Of primary interest in an environmental assessment are those effects which have a direct impact on human health and welfare as well as on the terrestrial environment and ecology. SPS-related effects occurring in the troposphere are therefore of significant interest, since the troposphere comprises the immediate environment in which human beings and a large number of other living species, both plant and animal, exist.

In contrast to many of the upper atmospheric effects, those which involve only the troposphere are all relatively localized. No *direct* tropospheric effects which would be expected to occur over a continental or larger scale have been identified. The effects which have been identified are associated with the use of large rockets [the heavy lift launch vehicle (HLLV) and the personnel launch vehicle (PLV)] to transport materials and personnel from the Earth's surface into orbit and with the use of large arrays (rectennas) of receiving elements for the ground-level reception of power transmitted from the satellites via microwave beams. Within a localized area surrounding the HLLV/PLV launch site or surrounding one of the rectenna sites, many of the effects identified and discussed in this paper would be detectable, and in some cases quite obvious to an observer. In no case, however, has an effect been found to be obviously unacceptable.

The scope of this discussion is limited to effects arising directly from rocket exhaust emissions associated with HLLV and PLV launches, and from the existence and operation of the rectennas. In addition, not all such effects are considered; for example, problems relating to the noise generated during the launching of large rockets are not considered here, nor are land-use questions associated with the construction of the rectennas. The increase in pollutant emissions associated with manufacturing and other industrial activities as well as with the related transportation emissions is also not considered.

Rocket exhaust emissions may affect the local environment in the vicinity of the launch site in several ways, all related to the development and subsequent evolution of the rocket ground cloud. The ground cloud consists of the exhaust emitted by the rocket during the first 15-20 s following ignition and liftoff, together with a large quantity of entrained air, cooling water, dust, and other debris. After the rocket has accelerated to an appreciable velocity, the exhaust products are deposited in a thin column that disperses quickly in the ambient air; no potentially significant effects have been identified with these emissions.

Immediately after formation, the ground cloud rises in the air owing to the buoyant effect of its high thermal energy content. Eventually, at an altitude typically between 0.7 and 3 km, the cloud stabilizes and is carried along by the prevailing wind at that altitude. As the cloud rises, much of the surface dust and debris falls out, the distance over which the fallout occurs being determined by the wind speed, by the nature of the turbulence within the cloud, and by the size of the particles. This distance may be as great as a few kilometers. At the same time, the upward convection motion of the ground cloud and the surrounding air may result in the formation of a water-saturated cloud. This phenomenon has been observed on several occasions. In addition, cloud microphysical processes may be affected by the production in the rocket exhaust of both cloud condensation nuclei (CCN) and ice-forming nuclei (IN).

The ground cloud also represents a source of air pollution and associated effects. The cloud disperses over a period of time, the rate of dispersion being determined by the level of turbulence both in the cloud itself and in the ambient atmosphere. Depending on the chemical nature of the rocket exhaust products, adverse environmental effects may or may not be produced at ground level. The reference design for both the HLLV and PLV[1] calls for the use of liquid methane and liquid oxygen in the first stage, instead of a solid propellant such as is used in most current rockets. The major exhaust products of the HLLV and PLV boosters are therefore carbon dioxide and water. Smaller quantities of nitrogen oxides, primarily nitric oxide and nitrogen dioxide, are expected to be produced from a possible molecular nitrogen impurity in the liquid oxygen or from entrainment and heating of ambient air in the hot rocket exhaust. In addition, possible impurities such as sulfur in the methane would give rise to a corresponding amount of oxidation products such as sulfur dioxide. As described below, sulfur dioxide due to a sulfur impurity in the hydrocarbon fuels currently in use has been measured in at least one ground cloud. This situation is significantly different from that of a solid-fuel booster, for which a major exhaust product is hydrochloric acid. Thus, for liquid-fueled rockets such as the HLLV and PLV, the potential air quality impacts must arise from substances present in relatively small amounts, the principal exhaust products being environmentally inocuous. The principal exhaust products of a solid-fueled booster would cause significantly greater environmental problems.

Presented as Paper 80-0884 at the AIAA International Meeting & Technical Display "Global Technology 2000," Baltimore, Md., May 6-8, 1980; submitted June 11, 1980; revision received March 1, 1982. Copyright © American Institute of Aeronautics and Astronautics, Inc., 1980. All rights reserved.

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Two types of air quality effect will be considered below. One is the direct increase of the atmospheric concentration of gaseous air pollutants; the other is the increase in the amount of various materials which are deposited on the ground. In evaluating the latter effect, two deposition mechanisms must be considered: dry deposition, involving turbulent diffusion to the ground followed by absorption by vegetation or soils, and wet deposition, involving the absorption of gaseous or particulate materials into falling raindrops. The problem of acid rain falls into the latter category, although acidic substances are removed from the atmosphere by dry deposition as well and the quantity of real interest in this connection is the total flux of acidic material to the surface.

The general tropospheric effects of rocket launches are illustrated in Fig. 1.

Possible environmental effects arising from the existence and operation of the rectennas are for the most part meteorological in nature. The presence of a rectenna covering an area of approximately 100 km^2 would be expected to affect the airflow in its immediate vicinity, owing to differences between the rectenna area and the surroundings in aerodynamic or surface roughness and albedo. The surface roughness affects the vertical flux of momentum and thermal energy and the rectenna albedo affects the surface energy budget. The effects of these differences are considered below, and include changes in air temperature, local and mesoscale circulation patterns, and cloud population.

Many of the effects discussed in this paper were also considered in two workshops held in the fall of 1978 dealing with the effects of rectenna operation[2] and HLLV launches.[3] References should also be made to a preliminary assessment of the meteorological effects of rectenna operation conducted earlier.[4]

Air Quality Effects

The estimated initial ground cloud composition following the launch of an HLLV is given in Table 1. In preparing these estimates, the quantity of exhaust products involved was taken to be that generated during the first 15 s following ignition and liftoff, and all the molecular hydrogen and carbon monoxide present in the exhaust at the rocket engine nozzle was assumed to be converted to water and carbon dioxide by afterburning. In addition, the presence of a sulfur impurity in the fuel at the 0.05% level was assumed; this figure corresponds approximately to the average sulfur content of hydrocarbon fuels now in use. The actual level of a sulfur impurity in the proposed liquid methane fuel may be considerably lower.

The masses of the gaseous substances in Table 1 represent the contributions due to rocket exhaust and afterburning only; thus, for example, the actual water content of the ground cloud is determined by the amounts of cooling water and ambient water vapor entrained in the cloud, in addition to the exhaust contribution. The mass of particulate material represents an estimate of the amount of dust and debris remaining in the cloud after the first 3-4 min, during which the very large particles will fall out. The concentrations given for SO_2, NO, and NO_2 represent the maximum values actually measured in the ground cloud of an Atlas/Centaur rocket. In using the same values for the HLLV ground cloud, the assumptions are that the amounts of NO and NO_2 produced are in the same proportion to the total amount of exhaust in both rockets and that the exhaust is diluted with ambient air by the same factor, which is approximately 4600 based upon the maximum observed SO_2 concentration in the Atlas/Centaur cloud and the corresponding fuel analysis, which indicated a sulfur impurity of 0.047%.

The Atlas/Centaur measurements just referred to were carried out in connection with the launch which took place on Nov. 13, 1978.[5,6] Another series of measurements was made on a Titan III ground cloud a month later on Dec. 13.[7] A

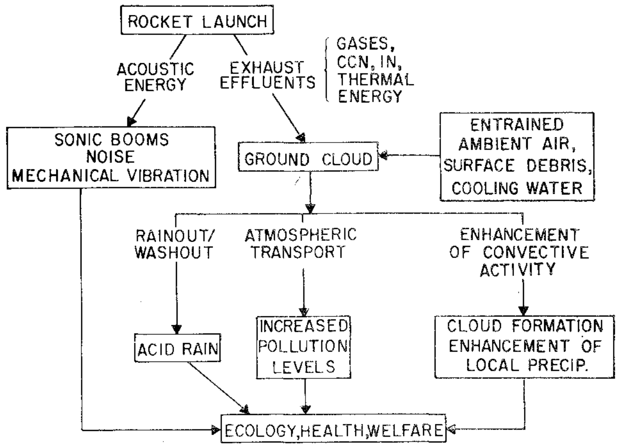

Fig. 1 Environmental effects of rocket launches.

Table 1 Initial ground cloud composition

Substance	Mass, 10^3 kg	Concentration, ppmV
H_2O	400-650	...
CO_2	450-700	23.0
SO_2	0.7-1.1	0.023
NO	9-14	0.64
NO_2	10-16	0.50
Particulates	0.02-2	...

total of 52 passes were made through the Atlas/Centaur ground cloud over a 2½-h period following the launch using an instrumented research aircraft. A variety of parameters was measured, including the concentrations of several gaseous chemical species, the particle size distribution, the CCN and IN concentrations, and the physical dimensions of the cloud. The maximum concentrations of NO, NO_2, and SO_2 were measured during the second pass, 5 min after liftoff (the aircraft did not travel through the center of the cloud during the first pass), and are given in Table 1 as indicated above. The cloud stabilized within an inversion layer between approximately 450 and 650 m above ground level, and remained at that altitude until it merged with an industrial plume approximately 2 h after launch. Dispersion of the cloud in the vertical direction was strongly limited by the inversion layer, and the contribution of the cloud to ground level concentrations was certainly negligible in this case. The cloud grew horizontally during the measurement period, and cloud concentrations decreased accordingly until at 110 min after launch, measured peak concentrations were 7 ppbV (parts per billion volume) (SO_2), 65 ppbV (NO_2), and 45 ppbV (NO). Systematic conversion of NO to NO_2 was observed as the cloud dispersed. This conversion may be attributed to the presence of ozone in the ambient air at a concentration of approximately 55 ppbV; as the ground cloud grew in size and entrained more and more ambient air, the ozone reacted with NO in the cloud, forming NO_2. This explanation is supported by ozone measurements in the cloud, which show that the ozone concentration is strongly depressed below the ambient level until the cloud is just barely detectable by other means. The rate of conversion is also in accord with independent measurements of the rate of growth of the cloud.

The Atlas/Centaur launch took place at 12:24 a.m. local time, i.e., shortly after midnight, and, as indicated above, the ground cloud stabilized within an inversion layer at about 500 m above ground. Meteorological conditions at night are often such that vertical dispersion of an elevated cloud is suppressed; under such conditions, ground level concentrations of substances in the ground cloud are below detection limits.

During the day, however, the level of atmospheric turbulence and the associated rate of dispersion may be very much higher, and the possibility of significant ground-level concentration of various substances from the ground cloud must be considered. The wind direction frequency in the vicinity of the launch site is an important factor in assessing the importance of ground-level pollutant concentrations. In the vicinity of Kennedy Space Center, Fla., a rocket ground cloud may drift over land approximately 50% of the time, based upon data presented in the KSC environmental impact statement.[8] This frequency should be kept in mind during the following discussion, which assumes that the ground cloud is over land.

The only substances present in the ground cloud of the Atlas/Centaur, and by analogy in the cloud from an HLLV, that are significant from an air quality point of view are SO_2, NO, and NO_2. As pointed out by Radke et al.,[5] the composition of the cloud was quite similar to that of a plume from a coal-fired electric power generating plant with defective control equipment burning low-sulfur coal. In order to put the expected environmental effects of an HLLV launch into perspective, it is useful to pursue this analogy. Table 2 presents the results of some recent measurements of the concentrations of SO_2 and NO_x ($NO_x = NO + NO_2$) in coal-fired power plant plumes. Comparison with Table 1 shows that the expected NO_x concentrations in an HLLV cloud are 3-4 times higher than those prevalent in power plant plumes, while a sulfur impurity of 0.05% will lead to SO_2 concentrations which are only 15-30% of those present in typical power plant plumes. In addition, the cloud elevation is comparable to plume elevations from large (1000 MW or more) power plants, and therefore the maximum ground-level concentrations of SO_2 and NO_x may be expected to be 15-30% and 300-400%, respectively, of those from a typical large power plant. It must be kept in mind, however, that the ground cloud represents a short, intense emission, whereas a plume represents a continuous emission. In order to compare effects, an averaging time must be introduced. In fact, the relevant averaging times are explicitly specified in the corresponding air quality standards. For example, the federal secondary standard for SO_2 specifies that the ambient SO_2 concentration averaged over a 3-h period should not exceed 500 ppbV more than once per year. Reference to Table 1 shows, however, that even the maximum SO_2 concentration in the center of the ground cloud is much less than this value. The conclusion is that any reasonable level of sulfur in the fuel will not give rise to significant ambient ground-level SO_2 concentrations, particularly when dispersion and cloud elevation are considered.

No short-term federal air quality standard currently exists for any of the nitrogen oxides. However, a 1-h standard for NO_2 of approximately 250 ppbV has been considered. Nitrogen dioxide is in fact rather toxic, although considerable debate exists about the biological effects of NO.[12] The problem that one encounters in attempting to predict NO_2 (and NO) concentrations is that both NO and NO_2 are reactive substances, and the common techniques used to predict atmospheric concentrations of air pollutants do not apply in this case. The NO_2 concentration is determined by the initial amounts of NO and NO_2 present in the cloud, by the extent of dispersion of the cloud, by the composition of the ambient air, particularly the ambient ozone level, and by the ambient light intensity. Nitrogen dioxide is continually photolyzed by sunlight to form NO and ozone, and at the same time NO and ozone react to re-form NO_2. The concentrations of all three species are determined by the relative rates of these competing processes. Calculations incorporating these effects indicate that the ground cloud by itself is unlikely to give rise to excesses of this standard at ground level; but the cloud contribution may not be negligible in some cases and, when added to the ambient level, an excess may occur. This possibility requires further investigation.

In addition, an excess amount of ozone above ambient levels has been observed within power plant plumes on a few occasions.[13-15] This phenomenon is not well understood at present, although there seems to be no reason why it cannot be accounted for using known chemistry. The possibility exists that a similar phenomenon might occur in the ground cloud from an HLLV in view of its chemical similarity to a power plant plume, although ground-level ozone concentrations would probably not be significantly affected.

Deposition of various chemical substances onto the ground may under some circumstances have adverse effects. In view of the discussion above, however, it does not seem likely that deposition in the vicinity of the launch site will be significant. The SO_2 concentrations are expected to be too small, and NO and NO_2 are not directly harmful when deposited over a short period of time corresponding to the passage of the ground cloud. Dissolution of SO_2, NO, and NO_2 in falling raindrops yields an acidic solution, but the acidity is due predominantly to the SO_2. Nitrogen oxides do not immediately form strongly acidic solutions, although over a several-hour period, a significant fraction may be converted to nitric acid. In this manner, NO_x emissions may contribute to an acid deposition/rain problem on a large spatial scale. No significant local effects are expected, particularly considering the intermittent nature of the deposition. The situation would be considerably different if a solid-fueled booster were used, since as indicated earlier a strong acid (hydrochloric acid) is a principal exhaust product of such a rocket.

Nitrogen oxides have been implicated in the large-scale acid rain problem in the northeastern United States,[16,17] as well as in the western United States.[18] In order to gain some insight into the significance of NO_x emissions from the SPS-related HLLV launches, it is again useful to compare these emissions to other, perhaps more familiar numbers. Table 3 presents some useful figures for this purpose. As can be seen, the total annual loading of NO_x due to 500 HLLV launches per year is only 44% of that from a typical power plant and only 30% of the estimated 1985 emissions from Brevard Company, in which the Kennedy Space Center is located. Based on these figures, it seems unlikely that the NO_x emissions from SPS-related rocket launches could have a significant effect on the large-scale acid rain problem. The same argument applies, of course, to any individual power plant or industrial source; the point is that the large-scale problem is due to the combined effect of a large number of such sources, whereas the given HLLV NO_x emissions themselves represent the entire total of direct concern in this assessment (neglecting the PLV emissions by comparison).

Table 2 SO_2 and NO_x concentrations in power plant plumes

Plant	Downwind Distance, km	Concentration, ppbV SO_2	NO_x	Reference
Labadie, Mo.	1.6	2.14×10^3	...	9
Charleston, W. Va.	1.6	4.35×10^3	...	9
Centralia, Ill.	0.8	...	4.2×10^2	10
Cunningham, N. Mex.	1.0	...	2.5×10^2	11

Table 3 NO_x emissions in perspective

Source	Annual NO_x emission, (10^6 kg)
HLLV (375 flights/year)	6.9
HLLV (500 flights/year)	9.3
1000-MW power plant[a]	21.2
Estimated 1985 KSC total[b]	0.3
Estimated 1985 Brevard Company total[b]	31.5

[a] Based on coal heating value of 8650 Btu/lb (low sulfur coal), 34% overall efficiency,0.55 load factor, emission factors from Ref. 19. [b] Reference 8.

Inadvertent Weather Modification

Rocket Exhaust

The assessment of the potential for inadvertent weather modification by the SPS rocket effluents is not easy at this time. The principal concerns are 1) the effects of a single ground cloud on the local weather, and 2) the cumulative effects of nearly 375 or more launches per year. Two major aspects which must be considered are 1) the immediate dynamical and thermodynamical response to the input of heat and moisture from the rocket exhaust for given ambient meteorological conditions, and 2) the alteration of the microphysical processes of clouds in the general area due to rocket effluents, debris, and cooling water entrained during the launch. The first aspect is relatively straightforward. Presumably one can use existing cloud models validated by previous rocket launch observations to simulate the convective activity and the possible associated precipitation. Such models require the initial thermal energy and total water content of the ground cloud and column cloud. However, measurements of these quantities are not generally available, and they must be estimated. The assessment of potentially significant inadvertent weather modification in terms of changes of cloud microphysical processes is similar to the assessment of planned weather modification. The degree of possible modification depends upon the time of year, the site location, the origin of the air mass, and the various scales of weather patterns. Unfortunately, the assessment of possible rocket related inadvertent modification is even more difficult because there have been few observations made that are relevant to both of the aspects discussed above during past rocket launches.

The central issue with regard to cloud microphysical processes is the possible production of cloud condensation nuclei and ice nuclei in the rocket-exhaust ground cloud. CCN serve as particles upon which water vapor condenses to form water droplets which in turn form clouds and fogs. They play an important role in determining the colloidal stability of clouds and the formation of precipitation. In general, the addition of CCN may tend to slow down the warm rain-formation processes (the precipitation formation processes in which ice plays no significant role) if the total CCN exceeds 10^3 cm^{-3}. However, if there are very large hygroscopic particles (giant nuclei with radii greater than 25 μm, such as are expected to come from launch pad debris) present, the rain-formation process may be accelerated. In the Florida area, some rainfalls are associated with condensation-freezing processes in a deep convection cloud system. In an IN-deficient, supercooled cloud, the addition of IN is expected to stimulate ice nucleation processes and lead to precipitation, although the effectiveness of this process is still a controversial subject. The global concentration of IN is about 1 $liter^{-1}$ at $-20°C$. In planned weather modification, an addition of approximately 10 effective IN $liter^{-1}$ is usually made at a supercooled cloud temperature of approximately -10 to $-15°$ C for precipitation enhancement, and one to several hundred IN $liter^{-1}$ are added for thunderstrom modification.

The recent measurement programs on Atlas/Centaur and Titan III ground clouds, referred to earlier, are both relevant to cloud physics. The Atlas/Centaur measurements indicated that the IN concentrations produced by the rocket launch had limited potential for weather modification. The potential modification due to IN production cannot be assessed with confidence at this time because of uncertainties in measurement techniques. The concentrations of CCN in the Atlas/Centaur ground cloud, however, were meteorologically significant. The initial emission was approximately 1.2×10^{17} CCN (active at 0.5% supersaturation), and later CCN were produced in the ground cloud at a rate of approximately 1 CCN cm^{-3} s^{-1}. Field and laboratory measurements[21,22] of a Titan III ground cloud indicated that both the IN and CCN concentrations were of meteorological significance. The initial emission of CCN from the Titan III was approximately 10^{18} (active at 0.5% supersaturation) and further CCN were produced at a rate of 0.5-1 CCN cm^{-3} s^{-1} for a period of 4 h after launch.[7] The high concentration of cloud condensation nuclei observed in both solid- and liquid-fueled rocket clouds could alter the frequency and persistence of fogs and haziness on the surface and the precipitation processes in warm clouds. The proposed HLLV would be liquid fueled. The exhaust products from this liquid propellant are not considered to produce effective ice nuclei; any IN present in the exhaust ground cloud would presumably be derived from debris and cooling water entrained during rocket launch. It is not possible at this time to estimate whether the HLLV would produce a significant number of effective IN in terms of weather modification potential.

In addition to these microphysical effects, the thermal energy and moisture contained in the rocket exhaust ground cloud are directly responsible for inducing a water-saturated, wet convective cloud and associated precipitation under certain meteorological conditions. The thermal energy provides sufficient buoyancy to lift the ground cloud and surrounding air to higher altitudes. During ascent, air cools through adiabatic expansion and, under certain conditions, reaches saturation to form a wet cloud. Subsequently, cloud convection is further enhanced through the release of latent heat, leading in some cases to precipitation.

In reviewing a motion picture of a ground cloud formed during the launch of Apollo 16 on April 16, 1972 at Kennedy Space Center, it was incidentally observed that a white, rapidly ascending, convective cloud formed at approximately 2 min after launch within the faintly visible brownish column of exhaust gas. This was followed by an optically dense convective white bubble penetrating through the top of the brownish ground cloud. Meanwhile, a natural cumulus cloud entered the circulation cell, descended, and dissipated within a couple of minutes. Atmospheric soundings of temperature and dew point at the time of launch indicate that the air, though dry (58% relative humidity near the surface and 83% at 2 km), was potentially unstable with a lifting condensation level at about 1.2 km. The temperature sounding indicated a near-adiabatic lapse rate up to 2 km altitude, where a dry, stable layer existed. The rocket engine was estimated to produce about 1.34×10^{10} cal/s.[20]

Perhaps the most unique data for a wet, saturated cloud generated by rocket thermal effluent are those obtained from the Titan III measurements referred to earlier. These data can be used for cloud model validation. The Titan III rocket produced saturated, white ground and column clouds. These clouds had the characteristics of a moderately sized, vigorous, cumulus cloud. Liquid water contents in excess of 1 gm^{-3} were measured in the column cloud 4 min after launch. Measurements of the ground cloud were taken after 25 min; they indicated that the ground cloud was saturated with a liquid water content of only 0.1 gm^{-3}. This wet phase of the ground cloud was detectable up to 51 min after launch, but only portions of the ground cloud were found to be saturated.

The proposed HLLV would emit 1.08×10^{11} cal s^{-1} of thermal energy to the atmosphere, a rate approximately 11 times greater than that of the Titan III. Model simulations, under the same meteorological condition, indicate that although the maximum updraft generated by the HLLV would be 4.3 times that generated by the Titan III, the maximum cloud water content in the HLLV ground cloud would only be 2.6 times that in the Titan cloud and, surprisingly, the duration of the saturated, wet phase would be shorter.

It should be noted that the above results should not be used to scale predictions of HLLV effects for all weather conditions. The degree of impact among various sizes of rockets varies from one meteorological condition to another. For example, under the meteorological condition of the Apollo 16 launch referred to earlier, quasi-steady-state convection clouds with similar intensities could be generated by all types of rockets in which the exhaust thermal energies are different by two orders of magnitude (such as the HLLV and the Atlas/Centaur). The predicted precipitations are slightly different in intensity for different types of rockets.

In view of the nonlinearity and the relative insensitivity of the results to the rocket energy output in some situations, a complete future assessment should include a climatology of the HLLV impacts for a given launch site for an updated HLLV design. The degree of cloud modification attributable to the launching of various rockets depends sensitively upon meteorological conditions. Generally, the conditions which favor onshore flow without strong westerlies above the planetary boundary layer are conducive to greater inadvertent weather modification in the Florida area by SPS rocket launches. Characteristic synoptic weather regimes that would fall into this category were identified for the Kennedy Space Center area in a theoretical study of Space-Shuttle exhaust clouds.[23]

Rectenna Operation

A preliminary assessment based upon the maximum microwave-beam power density of 230 W m^{-2} and an average waste heat release rate of 7.5 W m^{-2} from a rectenna covering approximately 100 km^2 was conducted in 1977.[4] The findings were that the effects of an SPS rectenna on weather and climate would be small compared to the direct environmental consequences of construction, and that the rectenna's influence would be similar to that of an average suburban development. In general, the intensity of the atmospheric perturbation due to SPS rectenna operation should be very small compared with that of other man-made installations. Microwave heating of the lower atmosphere through gaseous absorption would be negligible. Any actual effects of the microwave heating inside a cloud would not be detected in the presence of the natural variance of cloud and storm phenomena. Scattering by particles, even in a heavily polluted atmosphere, would also be negligible.

This initial study was reviewed at a workshop held in August 1978[2] and the conclusions updated. Three main topics were discussed: the effects of waste-heat release on the atmosphere at the rectenna site; microwave interactions with the atmosphere; and the possible effects of the microwave beam on atmospheric electrification processes. The following brief summary highlights the most important issues.

1. Rectenna Waste Heat and Structure

Construction of a rectenna would modify the thermal and radiative properties of the ground on which it is built; operations would introduce a heat source at the surface. Although the magnitude of the perturbation of the average surface heat budget would be on the order of 10%, microwave beam wandering and spreading due to atmospheric refraction may occasionally give rise to larger effects.

It is possible to investigate the effects of the rectenna by studying the effects of land-use changes. Small temperature changes (of the order of 1 deg) can be expected under light wind conditions. Changes in cloud populations can also be expected. Somewhat larger man-made dissipation rates over comparable areas have been associated with apparent anomalies in the distribution of rainfall.

In hilly terrain, on scales smaller than the rectenna dimensions, there are diurnally varying changes in the surface energy budget that are larger than the projected rectenna waste heat. It is therefore expected that the meteorological effects of a rectenna would vary from site to site, and the central maximum heat dissipation (approximately 16 W m^{-2}) might become important in augmenting a naturally occurring topographic effect.

Assessment of possible weather and climate effects over areas larger than the mesoscale should not be confined to the influence of the rectenna alone—it is necessary to consider the whole satellite power system in the context of the energy demand it is designed to meet. The overriding feature of the system is that the major inefficiency, the rejection of waste heat, is in space. Futhermore, there are no significant emissions of material into the troposphere during operation.

2. Microwave Propagation

The atmospheric absorption of microwave energy at the proposed SPS frequency is negligible in clear air for the projected tropospheric path lengths of about 20 km. However, some absorption by condensed water (clouds and precipitation) would occur when storms entered the beam path.

3. Atmospheric Electricity

Direct interactions with the atmospheric electric fields are not thought to be important at the proposed frequency. However, the mere physical presence of the rectenna might have some modifying influence on the occurrence and electrical behavior of thunderstorms over and around the rectenna.

In order to further examine the effects of the rectenna on local meteorological variables, a realistic simulation was performed for 24 h for a potentially unstable boundary layer with light winds over moist, flat ground.[24] Such a situation is conducive to the natural formation of cumulus clouds without precipitation. The simulation indicated that, excluding the effects of albedo changes, the major cause of the perturbation is the change in surface roughness rather than the release of waste heat. Air and soil temperature decreased during the daytime and increased only marginally at night. The increased mechanical mixing resulted in increased evaporation and absolute humidity, increased cloud amount, and decreased cloud-base height. The decrease in solar radiation resulting from the increase in cloud amount is greater than the waste heat term. The maximum rectenna-induced increase in the vertical velocity component was predicted to be only 0.5 cm s^{-1} at noon at 400 m about grade at the leading edge of the rectenna. The predicted extent of cloud modification would be much smaller if no difference in surface roughness existed.

A first examination of the combined effects caused by the rectenna waste heat, surface roughness, and radiative properties was done by a series of model simulations with various boundary conditions. The model was a three-dimensional, second-order turbulence closure equation set.[25] Meteorological conditions were selected for a typical daytime, unstable planetary boundary layer. No clouds were formed in this (dry convection) simulation. The results indicated that increased roughness over the rectenna area considerably increases the friction velocity (by a factor of 1.9) and decreases the surface wind speed (by a factor of 0.73) at the center of the rectenna area in comparison with values at the upstream boundary. The resulting convergence of horizontal wind causes a maximum vertical wind component of 7.2 cm s^{-1} about 10 km downwind from the rectenna center and 700 m above grade. If sufficient energy is available at the surface boundary, an increase in surface heat flux of up to a factor of 3.5 could result from enhancing vertical turbulent mixing due to the increase in surface roughness inside the rectenna area, without perturbing the surface temperature. Sufficient energy could presumably be made available by reducing the surface albedo; under the simulated conditions, however, unrealistically large surface albedo change would be required. The simulated heat fluxes at the upstream boundary and the rectenna center are 91 and 316 W m^{-2}, respectively. Inclusion of 8 W m^{-2} of waste heat would cause a surface temperature perturbation of only 0.06°C, a negligibly small value. These simulations should, by no means, be considered very realistic. However, the results do show that an increase in roughness results in more efficient transport of vertical turbulent fluxes without significantly increasing the surface temperature. Therefore it may be appropriate to conclude that surface roughness and albedo changes are the major causes of perturbation and that they may be of equal importance.

In examining the effects of the rectenna and its operation, consideration must also be given to the possible effect of the microwave beam itself, particularly owing to absorption in water droplets. Information regarding the amount of microwave absorption per unit path length as a function of rainfall rate is available.[26] With the most extreme rainfall rate of 254 mm/h as an example, the attenuation at the proposed 2.45-GHz frequency is estimated to be about 0.063 dB/km. At the proposed maximum power density of 230 W m^{-2} the absorbed microwave power inside the storm would be approximately 3.2×10^{-3} W m^{-3} which is approximately two orders of magnitude smaller than the release rate of the buoyant energy of a typical cumulus cloud. Therefore it is reasonable to conclude that the absorption of SPS microwave power by a storm will have no significant influence on cloud dynamics and thermodynamics and the associated precipitation.

Conclusions

No clearly unacceptable environmental effect of SPS-related activities in the troposphere has been identified. Possible effects which have been considered include increases in ground-level concentrations of air pollutants, increases in the deposition of rocket exhaust effluents, and the possibility of inadvertent weather modification due to the proposed high level of spaceflight activity, as well as meteorological effects of the construction and operation of the rectennas and the transmission of microwave power through the atmosphere.

Owing to the use of liquid methane as a fuel by the proposed space vehicles, the major rocket exhaust products are water and carbon dioxide; these substances have no adverse air quality effects in the troposphere. The possible presence of a sulfur impurity in the fuel at the 0.05% level will result in negligible air quality effects, since the maximum expected sulfur dioxide concentration in the rocket ground cloud is already less than the U.S. secondary SO_2 3-h standard. The ground cloud from a heavy lift launch vehicle may give rise to environmentally significant ground-level concentrations of nitrogen dioxide, although further work is required to quantify this possibility. Rocket launch emissions are expected to have a negligible effect on the rate of surface deposition of both direct exhaust products and acidic substances such as sulfates and nitrates which may be formed from them by atmospheric chemical reactions.

The huge amount of thermal energy contained in the exhaust of the proposed HLLV would in some situations induce a saturated, wet convective cloud or enhance existing convective activity. The degree and duration of these effects depend upon the ambient meteorological conditions. Generally, the effects would be more pronounced in potentially unstable air, which is conducive to natural cloud formation. Nevertheless, the effects would be limited to the general area of the launch site. The observed long-lasting high concentrations of cloud condensation nuclei produced during and after a rocket launch may appreciably affect the frequency of occurrence and persistence of fogs and haze. In view of the high mission frequency proposed for the satellite power system space vehicle launches, a potential exists for a cumulative effect. More studies are needed in this regard.

Analyses and model simulations in some chosen situations indicate that the weather/climate effect of the installation and operation of a rectenna is small, particularly outside the boundary of the structure. From the weather and climate points of view, construction of a satellite power system rectenna seems likely to have effects comparable with those due to other nonindustrial land-use changes covering the same area. The absorption and scattering of microwave radiation in the troposphere would have negligible atmospheric effects.

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